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# The fingerprint of the summer 2018 drought in Europe on ground-based atmospheric CO<sub>2</sub> measurements

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**Abstract.** During the summer of 2018 a widespread drought developed over Northern and Central Europe. The significant increase in temperature and the reduction of soil moisture have influenced the carbon dioxide (CO<sub>2</sub>) exchanges between the atmosphere and terrestrial ecosystems in various ways, such as a reduction of photosynthesis, changes in auto- and heterotrophic respiration, or allowing more frequent and/or stronger fires, which were particularly important in Sweden at the end of July 2018. In this study we characterise the resulting perturbation of the atmospheric CO<sub>2</sub> seasonal cycles. The year 2018 has an excellent coverage of the European regions affected by drought, allowing to investigate how large-scale ecosystem flux anomalies impacted spatial CO<sub>2</sub> gradients between stations in 2018. This density of stations is unprecedented compared to previous drought events in 2003 and 2015, particularly thanks to the deployment of the dense Integrated Carbon Observation System (ICOS) network of atmospheric greenhouse gas monitoring stations in recent years. Seasonal CO<sub>2</sub> cycles from 48 European stations were available for 2017 and 2018. Earlier data were retrieved for comparison from international databases or national networks. Here we show that the usual summer minimum in CO<sub>2</sub> mole fraction due to the surface carbon uptake was reduced by 1.4 ppm in 2018 for the 10 stations located in the area most affected by the temperature anomaly, mostly in northern Europe. Notwithstanding, the CO<sub>2</sub> transition phases before and after July were slower in 2018 compared to 2017, suggesting an extension of the growing season, with either continued CO<sub>2</sub> uptake by photosynthesis and/or a reduction in respiration driven by the depletion of substrate for respiration legated from the previous summer. For stations with sufficiently long time series, the amplitudes of the CO<sub>2</sub> anomaly observed in 2018 were compared to previous European droughts in 2003 and 2015. Considering the areas most affected by the temperature anomalies during these years, we found a higher CO<sub>2</sub> anomaly in 2003 (+3 ppm averaged over 4 sites), and a smaller anomaly in 2015 (+1 ppm averaged over 11 sites) compared to 2018.

## Keywords

35 Atmospheric CO<sub>2</sub> measurements, Net Ecosystem Exchange, Drought, Heatwave

## 1 Introduction

Continuous atmospheric carbon dioxide (CO<sub>2</sub>) measurements from ground-based networks, in combination with atmospheric inverse models, allow us reducing uncertainty in estimated surface fluxes. These inverse models are

used to optimise fluxes to best fit the atmospheric observations given simulated transport, and in most cases, given a prior estimate of fluxes and their uncertainty. Atmospheric inversion models are comprehensive systems that provide optimized fluxes and their error statistic to best represent observed atmospheric concentrations. Generally, they assign uncertainties to atmospheric observations that are much larger than the instrumental uncertainty, to account for transport model uncertainties [1, 2]. A valuable alternative is the direct analysis of spatial and temporal gradients in atmospheric CO<sub>2</sub> concentration measurements alone, to detect inconsistencies with, e.g., regional climate anomalies that are expected to impact CO<sub>2</sub> fluxes. This approach is qualitative, and it does not quantify the fluxes, but it provides a preliminary data analysis before inversions.

The first goal of this study is to present the most complete up-to-date, unpublished dataset of CO<sub>2</sub> atmospheric concentration measurements across Europe. Data of the harmonised Integrated Carbon Observation System (ICOS) have only become available in the most recent years, and have been combined with records from the same stations that were in operation before the implementation of ICOS, and with records from additional non-ICOS stations from regional and national networks. In this study, we carefully selected only stations that ensure a traceability of their measurements to the international World Meteorological Organization (WMO) CO<sub>2</sub> mole fraction scale [3, 4]. The total number of sites with continuous, harmonized data is 48 stations in the year 2018, and cover the period from 1971 to end of 2018. The second objective is to analyse the observed CO<sub>2</sub> concentration anomaly across different sites during the growing season of 2018 compared with previous years, mainly 2017, to answer the following question: can a dense atmospheric measurement network be used to directly detect the space-time patterns of CO<sub>2</sub> flux anomalies during the widespread and intense 2018 spring and summer drought event that prevailed over Western and Central Europe?

## 2 The measurement stations

All atmospheric measurement stations operating continuous CO<sub>2</sub> measurements in 2018 are shown in figure 1. A total of 48 stations covering Western, Southern and Central Europe, and Nordic countries (Table 1) are included. This network has a mean density of about 12 stations per 10<sup>6</sup> km<sup>2</sup> in the area of the countries that have at least two stations. There is no coverage in Belarus, Russia, or any country in the Balkans. The median distance between one stations and its three closest neighbors ranges from 60-80 km for stations located in the Alps (LHW, JFJ, BRM, PRS) to more than 1300 km for ZEP, FKL, and IZO, and is equal to 385 km on average. The stations are located at tall towers in rural areas, mountain sites, coastal locations, and, in few cases, in urban or sub-urban locations. Only twelve stations provided continuous data in 2009, in contrast to forty-eight in 2018. Tall tower measurements are generally made from two to five sampling levels ranging from 2.5 to 341 m above the ground level. The present dataset contains 20 tall tower stations, which sums up to 68 time series corresponding to all sampling levels (Table 1). In total, more than 5 million hourly averages of atmospheric CO<sub>2</sub> concentration have been collected for this study. Depending on sites and time periods, data have been collected from different repositories (Supplementary Figure S1), namely: the National Oceanic and Atmospheric Administration's (NOAA) OBSPACK compilation (29%) [5], ICOS (26%), the World Data Centre for Greenhouse Gases (WDCGG) (5%), and from the scientists in charge of individual sites (40%). Concentrations from flasks sampled on a weekly basis by ENEA institute [6] have been used only at Lampedusa in order to fill in a data gap from February to May 2018 at this station. The European research infrastructure ICOS is engaged in a process of standardisation of measurement

protocols, quality control and data processing for European stations [7, 8]. Since ICOS became operational in late 2017, data underwent a standardized processing and a stringent quality control. The ICOS network represents a homogeneous subset of the European network (up to 55% of the total dataset in 2018), whose data is easily available through the ICOS Carbon Portal ([www.icos-cp.eu](http://www.icos-cp.eu)), with high traceability, and it has been thoroughly evaluated by the ICOS scientific community. Data from the international repositories were checked for consistency prior to ingestion into the databases. Data from individual stations were validated by the responsible scientists. All measurements presented in this study are referenced to the international reference scale WMO-X2007 [4, 9], and can be downloaded from the ICOS Carbon Portal (DOI: 10.18160/ere9-9d85).

Data availability and the temporal coverage of the data from 2008 to 2018 are represented in figure 2. The longest records are from Schauinsland, Germany (since 1971) and Monte Cimone, Italy (since 1979), and the shortest are from recently installed ICOS sites like Norunda (January 2017) and Svartberget (June 2017) in Sweden. New ICOS sites that have become operational since summer 2018, were not included in this analysis due to the measurement period being too short. Rates of missing data during the measurement period can be classified in three tiers: more than 20% (in the period 2009-2018 and in 2018 only, 30 and 38 stations, respectively), between 10 and 20% (8 and 4 stations, respectively) and less than 10% (10 and 6 stations, respectively). A total of forty four stations cover the growing season of the year 2018 defined as the period from beginning of April to end of October. Out of these, 22 stations are located in an area affected by a  $1.5\text{-}\sigma$  anomaly, or more, compared to the 2009-2018 period, at least for one month in summer 2018, based on  $0.25^\circ$  gridded climate ERA5 reanalysis data [10].

### 3 Analysis of the atmospheric CO<sub>2</sub> seasonal cycle across Europe

We applied a data selection scheme to all time series in order to minimise the effects of local contributions, and increase the spatial representativeness of each record. Except for Mace Head (MHD), where we used a selection scheme based on wind speed, direction, and hourly standard deviation of CO<sub>2</sub> [11], we have applied a simple selection to all stations. It consists of retaining mid-afternoon (12-17h local winter time) data at tall tower and coastal stations, and retaining night-time (20-05h local winter time) data to mountain stations, when the air is well-mixed, providing a large spatial representativeness with minimum influence from local sources [12-14]. In addition to this temporal filtering we also excluded hourly means with standard deviation greater than 0.5 ppm from the selected time series. As a consequence, this data selection significantly reduces the number of hourly averages (26% of the total), but only marginally affects the number of daily averages (by 5.5% on average). From the selected dataset, we have estimated the seasonal cycles of atmospheric CO<sub>2</sub> concentration by using the curve fitting procedure developed by Thoning *et al.* (1989) [15]. For each station, the CO<sub>2</sub> time series are fitted with a 4-harmonics curve and a quadratic polynomial function. Residuals from this fit are filtered in the time domain using a low-pass filter in order to separate high-frequency variations and inter-annual variabilities.

Figure 3 shows selected hourly measurements, as well as the corresponding smoothed curves from four tall tower sites: Hyltemossa (HTM, Sweden), Gartow (GAT, Germany), Tacolneston (TAC, UK) [16], and Observatoire Pérenne de l'Environnement (OPE, France) [17]. The smoothed curves are compared to the one inferred from the marine sector selection at Mace Head, which can be chosen as a marine background station for air masses advected into the European continent, a site commonly used as a background reference for Western Europe [18]. The signals

observed at these four stations are typical for rural sites. They are characterised by strong positive synoptic CO<sub>2</sub> events in the winter half-year from September to early March, when CO<sub>2</sub> concentration is at the higher part of its seasonal cycle. These episodes correspond to periods of low-atmosphere stratification, leading to an accumulation of gases emitted at the surface in the atmospheric boundary layer. In the case of CO<sub>2</sub>, the emissions in the non-growing season originate from both anthropogenic and biogenic sources. This corresponds to the period with CO<sub>2</sub> concentrations at the European sites larger than marine background concentrations measured at Mace Head. In contrast, CO<sub>2</sub> concentrations at inland stations are lower than those at Mace Head from March to July, due to the influence of CO<sub>2</sub> absorption by European ecosystems, which dominates the continued anthropogenic emissions at the continental scale. Note that there is no symmetry between the amplitude of the winter peaks, and the negative peaks of spring, mainly because of limited vertical development of the atmospheric boundary layer in autumn/winter [19, 20] which amplifies the atmospheric signals measured at the surface during those seasons. Additionally, in winter both anthropogenic emissions and biogenic emissions contribute to positive synoptic anomalies, whereas in summer they mainly offset each other. Only clean air masses that did not receive recent anthropogenic emissions while being exposed to CO<sub>2</sub> uptake can create negative synoptic CO<sub>2</sub> anomalies [21-23].

Over the 2009-2018 period, we calculated the amplitude of the seasonal cycle as the difference between the smoothed monthly mean maximum in winter and the minimum in summer. The largest and smallest amplitude were observed at the urban site of Heidelberg (32 ppm), and at the background marine site of Izaña (7.8 ppm), respectively. In addition to its marine footprint, the smaller amplitude at the latter station is due to its location south of continental Europe. At Mace Head, the CO<sub>2</sub> amplitude for oceanic air masses is on average 14.9 ppm. Overall, we may distinguish between the coastal sites like Mace Head (12 sites), which display an average annual amplitude of  $14.5 \pm 3.0$  ppm, the mountain sites (7 sites) with an amplitude of  $12.4 \pm 2.0$  ppm, and the highest sampling levels of the tall towers (20 sites) with a mean amplitude of  $21.0 \pm 3.0$  ppm.

#### **4 Atmospheric CO<sub>2</sub> concentrations fingerprint of the 2018 European summer climate anomaly**

The climate anomaly in Europe during 2018 was characterised by temperatures higher than normal for every month from April to December, and by a sustained dry period from June to November in Central Europe, with a fast transition from normal to drought conditions from spring to late spring and summer [24-26]. Europe experienced late spring and summer temperatures that were more than 1 °C warmer than 1981–2010 [27, 28], with the highest temperature anomalies (+2.5°C) being observed in May-June. Most of Europe was affected, but the anomaly was particularly marked in Central and Northern Europe. In Southern Europe, particularly the Iberian Peninsula, the conditions in summer and spring were wetter than usual and likely promoted stronger biospheric CO<sub>2</sub> uptake. In this region, crop yields were found to be higher than normal during 2018, whereas low and extremely low yields were recorded in Central and Northern Europe [25, 29].

The atmospheric CO<sub>2</sub> seasonal cycle observed at the top level of four tall towers located in the UK, France, Germany and Sweden, were clearly affected by the drought in 2018 (Figure 4). For all four sites, we observe a similar pattern during the summer of 2018. While the overall pattern compares well with previous years, the CO<sub>2</sub> drawdown, normally observed between March and August, was reduced between June and August 2018. In comparison with the average of the previous years (see the periods on figure 4), the occurrence of the daily concentration minimum in summer 2018 was delayed by 12, 13, 28 and 32 days for OPE, GAT, TAC and HTM,

respectively. For these four sites, the mean CO<sub>2</sub> anomaly (2018 minus the average of previously available years) was  $1.7 \pm 0.2$  ppm and  $1.3 \pm 0.5$  ppm in July and August, respectively, which corresponds to 17% and 12% of the mean CO<sub>2</sub> drawdown (defined as the annual minimum value). Figure 5 shows the mean CO<sub>2</sub> anomaly for all the sites whose data are part of this analysis. Among the 20 tall towers, only a few did not see a positive anomaly during the months of July and August (BRM, Switzerland; HPB, Germany; IPR, Italy in July; and BIK, Eastern Poland in August). The average concentration anomaly in July-August, taking into account the 20 tall towers (highest sampling levels), is  $0.9 \pm 0.8$  ppm in July, and  $1.3 \pm 0.7$  ppm in August. It is significantly lower at the seven mountain sites ( $-0.4$  and  $+0.6$  ppm in July and August, respectively), as they are less exposed to regional scale vegetation-atmosphere CO<sub>2</sub> exchange (Supplementary Figure S2). From our analysis, we conclude that nearly all stations located on the European continent show reduced CO<sub>2</sub> seasonal amplitudes from spring to late summer in 2018 compared to 2017. Because fossil fuel CO<sub>2</sub> emissions were similar in these two years across European countries [30, 31], this anomaly must reflect a weaker net CO<sub>2</sub> uptake during this period, possibly coupled with weather-related atmospheric CO<sub>2</sub> enrichment. In particular, the July-August period of 2018 saw an increase in the number of days where European weather conditions were dominated by Scandinavian blocking regimes relative to 2017 [32-34]. Twenty-two such days occurred in July-August of 2018, as opposed to only nine for the same period in 2017. This also represented a significant increase over the July-August average of  $\sim 14.2$  days for the 2009-2017 period. Blocking conditions due to sea-level pressure (SLP) anomalies over the North Atlantic promote CO<sub>2</sub> accumulation, since persistent anticyclonic flow tends to transport CO<sub>2</sub>-enriched air into central and Western Europe from the Eurasian interior.

It is also noticeable that lower than average CO<sub>2</sub> concentration in spring and autumn 2018 (Figure 5) were observed at most measurement sites. This difference in CO<sub>2</sub> concentration is  $-0.7 \pm 0.6$  and  $-1.3 \pm 0.9$  ppm for the months of May and September 2018 if we only consider the 10 stations located in the area where the mean temperature anomaly in summer is larger than  $1.5 \sigma$  of the 2009-2018 average. The negative difference in spring is likely related to an earlier onset of the growing season and enhanced photosynthesis, promoted by extremely warm conditions and increased solar radiation [24, 25]. In autumn, the negative differences in CO<sub>2</sub> concentration may reflect either a prolonged growing-season, as temperatures remained high, but also possibly a reduction in respiration due to summer productivity collapse. The results discussed above were obtained from atmospheric CO<sub>2</sub> concentrations selected during daytime for all lowland stations, when the atmospheric boundary layer is well developed. Nighttime measurements have a significantly reduced footprint due to the lower atmospheric mixing, and they are not used in atmospheric inversions that have trouble representing the nighttime boundary layer. We therefore analyzed the CO<sub>2</sub> diurnal cycles by calculating each day the difference of the nighttime concentrations (01-05 h LT) compared to daytime values (12-16 h LT). From the four tall towers shown in Figure 6, those differences oscillate between values close to 0 in winter, and maximum values (2 to 10 ppm) in May-June. The purpose of this analysis is mainly to verify if the amplitude of the diurnal cycles has been modified in 2018 compared to previous years. The anomaly 2018 of this signal is represented on the bottom panel of Figure 6. In general, there is an increase in the amplitude of the diurnal cycle in spring, and a decrease in summer. The closer you get to the surface, the more amplified this signal is due to the stronger influence of the surface sources in the tower's footprints. Overall, looking at the tall towers located in the area the most affected by the drought, the average amplitude of the daily cycle observed at elevation greater or equal to 100m a.g.l., is increased by  $0.4 \pm 0.9$  ppm in May 2018, and reduced by  $-2.0 \pm 0.8$  ppm in July 2018. For the same sites, if we select only observations

below 100 m a.g.l. the 2018 anomaly is  $1.1 \pm 2.9$  ppm in May and  $-3.4 \pm 2.0$  ppm in July. The reduction of the CO<sub>2</sub> daily amplitude in July can be due to an increase of the daytime concentrations associated to the reduction of the surface uptake by ecosystems, and/or a decrease of nighttime concentrations. Considering that these values are greater than the anomaly calculated solely from afternoon data, it seems that this signal points to a significant contribution of ecosystem respiration, which is also the conclusion from observations at ICOS eddy-covariance sites [24].

We have applied the same analysis to the column-averaged dry air mole fractions of CO<sub>2</sub> (XCO<sub>2</sub>) observations at the TCCON (Total Carbon Column Observing Network) site of Sodankylä in northern Finland, where measurements have been made since 2009 [35]. Compared to the surface measurements, the amplitude of the seasonal cycle of XCO<sub>2</sub> measurements is smaller (9.8 ppm on average). This is due to the fact that the column-averaged mole fraction is almost insensitive to vertical transport. But nevertheless, the minimum monthly XCO<sub>2</sub> also occurs in August due to the uptake of carbon into the biosphere [35] at this TCCON site. In 2018 we observed a similar pattern for XCO<sub>2</sub> compared to the surface stations, with higher concentrations in July and August by +0.6 and +0.4 ppm, respectively, and lower concentrations in September and October by -0.5 and -0.8 ppm respectively (Figure 7).

The average CO<sub>2</sub> differences deduced from the measurement network mask regional disparities, because the 2018 drought was not uniformed throughout the European continent [24, 25]. In order to visualise the regional patterns of the atmospheric CO<sub>2</sub> anomaly, we mapped the detrended CO<sub>2</sub> differences observed from May to September 2018 compared to the previous year (Figure 8a), and compared to the average of the seven previous years where data are available since 2010 (Figure 8b). The first comparison benefits from the very recent development of the measurement network which allows a representation of CO<sub>2</sub> concentrations with a high density of measurement points, while the second makes it possible to compare the measurements of 2018 with an average over a more representative period. Figure 8a clearly shows the development of a positive CO<sub>2</sub> difference (2018-2017) of around 2 to 4 ppm in July / August in the central and northern part of Europe. For the northern part of Europe (UK, Benelux, northern Germany and Scandinavia) the CO<sub>2</sub> differences between 2018 and 2017 switch to negative values (-2 to -4 ppm) in September / October. However, this is not the case for stations located further south, where the 2018-2017 differences remain positive. When looking at the sites with longer time series (Figure 8b), this latter signal goes very close to zero, which is not the case for the positive / negative signals observed in the Northern part of Europe.

## **5 Comparison of the 2018 climate anomaly with previous European droughts**

Due to the relatively recent expansion of the monitoring network, it is difficult to compare the signals observed in summer 2018 with previous drought events. In addition, the geographical extension of the droughts recorded in Europe in 2003, 2015 and 2018 do not overlap, therefore not all the same stations have been affected [26, 36]. However, it remains possible to compare the amplitudes of the CO<sub>2</sub> anomalies observed in 2018 and during previous droughts in 2003 and 2015. The heat wave of 2003 had dramatic health consequences in Western Europe, and in terms of carbon cycle, Ciais et al., (2005) estimated a 30% reduction in gross primary productivity over Europe, which resulted in a strong anomalous net source of carbon dioxide (0.5 Pg C) to the atmosphere [37]. This study was based on ecosystem observations and models but did not use information provided by the limited



existing atmospheric CO<sub>2</sub> records. Compared to 2018, the 2003 drought was more centred on Western and Southern Europe [37]. The dataset compiled as part of this study includes 8 stations from the most affected region in 2003 (Figure S3). Five of them are located in an area significantly affected by the heat wave of August 2003 (anomaly of the mean temperature  $>1.5\sigma$  of the 2009-2018 average). Among these five stations, one (CBW) provided no data from June 17 to August 15, 2003, and is therefore not taken into account in the present analysis. At the other four stations the CO<sub>2</sub> concentration anomaly is greater than 2 ppm (4.5 ppm at SSL, 2.1 ppm at CMN, 2.7 ppm at HUN, 2.6 ppm at HEI) in 2018, and the average anomaly is  $+3.0 \pm 1.1$  ppm in August 2003 (Figure 9, S3). In July 2018, for comparison, if we exclude the 12 coastal/ oceanic stations, ten stations out of a total of 36 are located in a temperature anomaly zone following the same criterion ( $>1.5\sigma$  of the 2009-2018 average). The average CO<sub>2</sub> anomaly of those ten sites in July and August 2018 is  $+1.3 \pm 0.4$  ppm and  $+1.4 \pm 0.5$  ppm, respectively. It is interesting to note that both in 2003 and 2018, the atmospheric CO<sub>2</sub> records indicate a reduction of the CO<sub>2</sub> uptake in summer associated with the droughts, but, on the contrary, an apparent increase of the uptake in the preceding spring and following autumn. In spring 2018, the anomaly averaged over the ten stations located in the drought zone is  $-0.7 \pm 0.6$  ppm in May 2003, and is  $-0.3 \pm 0.7$  ppm (4 sites) in June 2003. Similarly, the autumn anomaly in 2018 reaches  $-1.3 \pm 0.6$  ppm in September 2018 (10 sites) (Figures 4, 5, 8), and  $-2.6 \pm 2.5$  ppm in October 2003 (4 sites) (Figures 9, S3).

The temperature anomaly in summer 2015 mainly affected Southern Europe in July, and Central Europe in August. Only two CO<sub>2</sub> stations in Poland were located in the heart of the temperature anomaly in August 2015, and CO<sub>2</sub> anomalies of +0.4 and +3.4 ppm were observed at BIK and KAS, respectively (Figures 10, S3). In July, 11 of the 29 non-coastal stations measuring in 2015, were located in the temperature anomaly area ( $>1.5 \sigma$  of the 2009-2018 average). The CO<sub>2</sub> anomaly recorded by these stations was on average  $+1.0 \pm 0.6$  ppm (Figure S3). The CO<sub>2</sub> anomaly observed in the summer of 2015 at stations in southern Europe had, therefore, less impact on the biospheric uptake than in 2003 and 2018, and no significant negative anomaly is observed in spring and autumn.

## 6 Conclusions

In the context of the 2018 drought study, we have merged the largest ever data set on atmospheric CO<sub>2</sub> concentrations in Europe, with 48 measurement sites, including 20 tall towers sampling air at several levels above the ground. Heights. This dataset, made available via the ICOS Carbon Portal (DOI: 10.18160/ere9-9d85), goes well beyond the 2018 drought study, since it includes the historical measurement series of the involved stations. It has already been used in three atmospheric inversions aiming to determine the impact of the 2018 drought on CO<sub>2</sub> exchanges with terrestrial ecosystems [14, 24, 36]. The objective of this study was to characterize the anomaly of CO<sub>2</sub> concentrations observed over the European continent in 2018, and to compare it with previous droughts. Taking into account the sites located in the areas most affected by the 2018 drought [25], in Central and Northern Europe, it appears that the seasonal minimum of CO<sub>2</sub> in summer (July-August) has been reduced by  $1.4 \pm 0.5$  ppm (12% of the seasonal minimum). It is difficult to compare the impact of different droughts with each other because of the geographical diversity of these droughts, as well as the smaller number of stations available as time goes by. However, by selecting stations located in areas where temperature anomalies are at least 1.5 sigma relative to climatology, the impact of the 2018 drought on CO<sub>2</sub> concentrations is found to be between those of 2003 ( $3.0 \pm 1.1$  ppm) and 2015 ( $1.0 \pm 0.6$  ppm). It should be noted that the apparent decrease in carbon absorption in the summer

of 2018 appears to be partially offset by an apparent higher absorption in the spring and autumn of the same year. Making the difference in this atmospheric signal between the contributions of atmospheric transport (droughts are accompanied by an increase in anticyclonic blocking conditions), and the different components of the biospheric fluxes (gross primary productivity, ecosystem respiration, biomass burning) remains a difficult challenge. To go further in the interpretation, it will be important to develop the use of other atmospheric compounds, such as CO, CH<sub>4</sub>, Radon-222, COS, isotopes. The correlations of these compounds with CO<sub>2</sub> will provide information allowing, for example, to normalize the influence of the large-scale atmospheric circulation in Europe that affects all atmospheric compounds, or to quantify the intensity of biomass burning (e.g. CO, black carbon). For this purpose, the establishment of a dense network of atmospheric observatories in Europe, dedicated to multi-compound measurements, and anchored in the long term thanks to research infrastructures such as ICOS and ACTRIS is essential to improve our understanding the impact on our environment of extreme events, such as droughts and heatwaves, likely to intensify in the decades to come.

## Acknowledgements

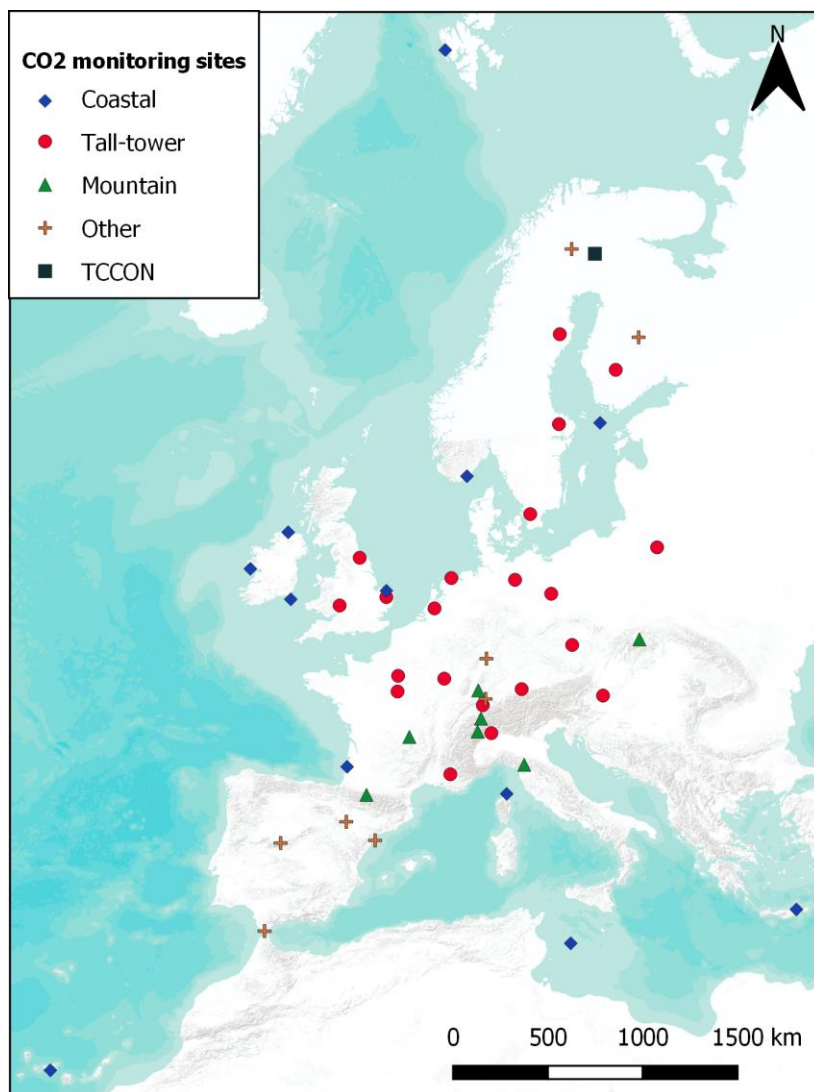
The authors acknowledge all the technical staff in charge of operating the atmospheric stations. ICOS activities at CMN have been implemented by the National Project of Interest NextData and are supported by the Ministry of Education, University and Research; CNR acknowledges the logistic support and hospitality of Italian Air Force “CMM”. The UK sites were funded by the UK Department of Business, Energy and Industrial Strategy (formerly the Department of Energy and Climate Change) through contracts TRN1028/06/2015 and TRN1537/06/2018. The Cabauw measurements have been supported by the Dutch government as well as national and European projects. The Hegyhatsall measurements have been supported by the Hungarian Meteorological Service. For Bialystok, we would want to acknowledge the support of the Max Planck Society. Measurements at Lampedusa were supported by the Italian Ministry for University and Research through project NextData and the ICOS-Italy Joint Research Unit. The stations at the ClimaDat Network in Spain have received funding from the “la Caixa” Foundation, under agreement 2010-002624. Thanks to the people from the Parc Científic of Barcelona (PCB-UB), the Catalan Institute of Climate Sciences (IC3), and the Institut de Ciència i Tecnologia Ambientals (ICTA-UAB) who contributed to ClimaDat: M.A. Rodríguez-Arias, A. Font, I. Pouchet, A. Águeda, R. Arias, L. Sánchez, P. Occhipinti, M. Tello, S. Liñan, Ò. Batet, M. Nofuentes, C. Grossi, M. Ealo, S. Borrás, L. Cañas, E. Vázquez, A. Jornet, À. Garriga, C. Estruch. The French monitoring network acknowledges the long term support received as part of the Service National d'Observation program. Thanks to V. Legendre, P. Wiszniowski, L. Gest, P.Y. Quéhé, J. Helle, T. Laemmle, L. Valettes, A. Orgun, R. Jacob, D. Combaz, C. Lett, O. Llado, C. Peureux, C. Vuillemin, F. Truong. B. Gal.

**Table 1.** List of stations with their coordinates and sampling heights

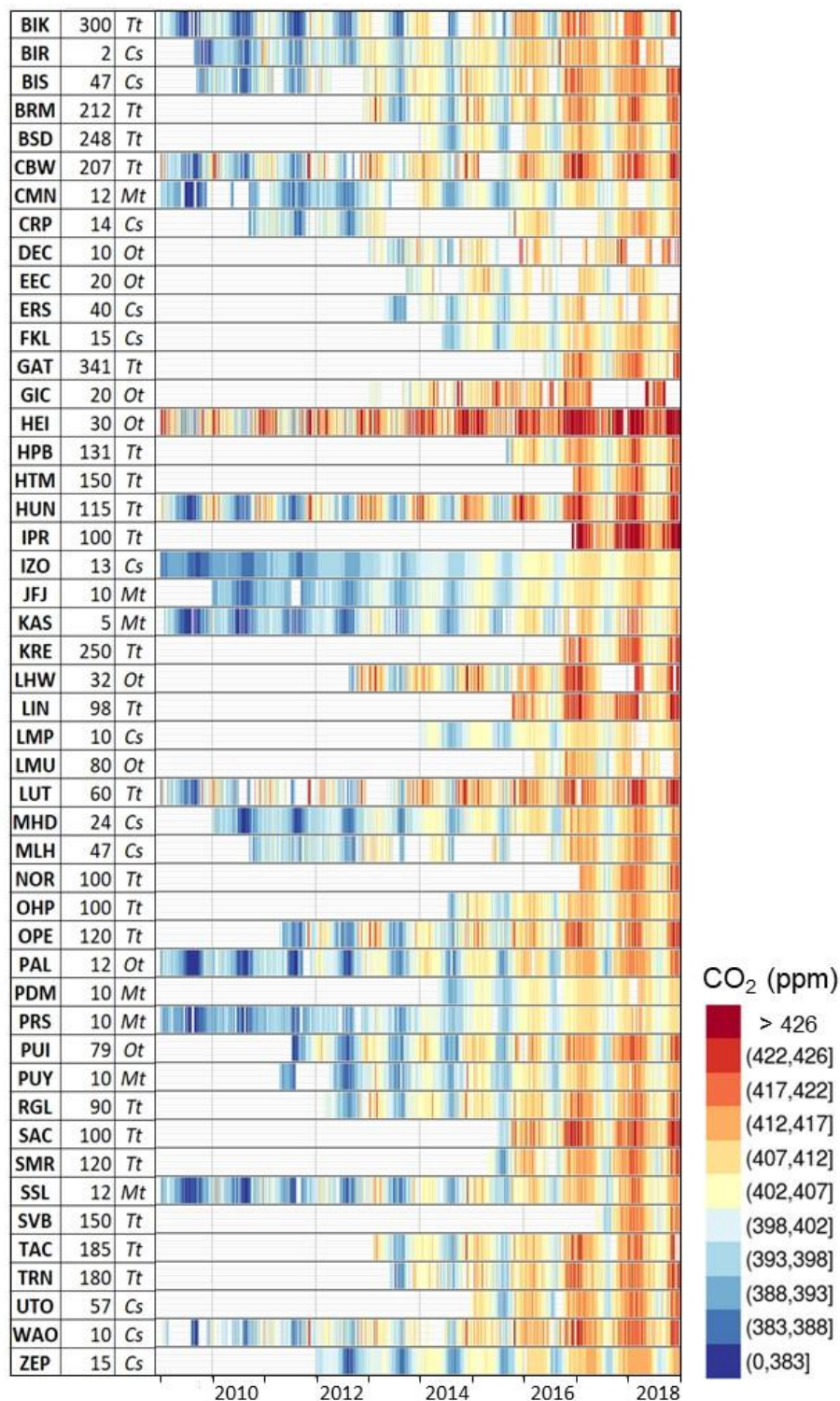
ID	Station	Country	Lat [°]	Lon [°]	Alt [m.a.s.l.]	Inlet [m.a.g.l.]
BIK	Białystok	Poland	53.2320	23.0270	183	5, 30, 90, 180, 300
BIR	Birkenes	Norway	58.3886	8.2519	219	2.5
BIS	Biscarrosse	France	44.3781	-1.2311	73	47
BRM	Beromünster	Switzerland	47.1896	8.1755	797	12, 45, 72, 132, 212
BSD	Bilsdale	United Kingdom	54.3590	-1.1500	380	42, 108, 248
CBW	Cabauw	The Netherlands	51.9710	4.9270	-1	27, 67, 127, 207
CMN	Monte Cimone	Italy	44.1667	10.6833	2165	8, 12
CRP	Carnsore Point	Ireland	52.1800	-6.3700	9	14
DEC	Delta de l'Ebre	Spain	40.7439	0.7867	1	10
EEC	El Estrecho	Spain	36.0586	-5.6640	20	20
ERS	Ersa	France	42.9692	9.3801	533	40
FKL	Finokalia	Greece	35.3378	25.6694	250	15
GAT	Gartow	Germany	53.0657	11.4429	70	30, 60, 132, 216, 341
GIC	Sierra de Gredos	Spain	40.3457	-5.1755	1436	20
HEI	Heidelberg	Germany	49.4170	8.6740	116	30
HPB	Hohenpeissenberg	Germany	47.8011	11.0246	934	50, 93, 131
HTM	Hyltemossa	Sweden	56.0976	13.4189	115	30, 70, 150
HUN	Hegyhatsal	Hungary	46.9500	16.6500	248	10, 48, 82, 115
IPR	Ispra	Italy	45.8147	8.6360	210	40, 60, 100
IZO	Izana	Spain	28.3090	-16.4990	2372.9	13
JFJ	Jungfraujoch	Switzerland	46.5500	7.9870	3570	10
KAS	Kasprowy Wierch	Poland	49.2325	19.9818	1989	5
KRE	Krešín u Pacova	Czech Republic	49.5830	15.0800	534	10, 50, 125, 250
LHW	Laegern-Hochwacht	Switzerland	47.4822	8.3973	840	32
LIN	Lindenberg	Germany	52.1663	14.1226	73	2.5, 10, 40, 98
LMP	Lampedusa	Italy	35.5300	12.5200	45	10
LMU	La Muela	Spain	41.5941	-1.1003	571	80
LUT	Lutjewad	The Netherlands	53.4036	6.3528	1	60
MHD	Mace Head	Ireland	53.3261	-9.9036	8	24
MLH	Malin Head	Ireland	55.3550	-7.3330	22	47
NOR	Norunda	Sweden	60.0864	17.4794	46	32, 59, 100
OHP	Obs. de Haute Provence	France	43.9310	5.7120	650	100
OPE	Obs. pérenne de l'environnement	France	48.5619	5.5036	390	10, 50, 120
PAL	Pallas	Finland	67.9733	24.1157	565	5, 12
PDM	Pic du Midi	France	42.9372	0.1411	2877	10, 28
PRS	Plateau Rosa	Italy	45.9300	7.7000	3480	10
PUI	Puijo	Finland	62.9096	27.6549	232	79, 84
PUY	Puy de Dôme	France	45.7719	2.9658	1465	10
RGL	Ridge Hill	United Kingdom	51.9976	-2.5000	204	45, 90
SAC	Saclay	France	48.7227	2.1420	160	15, 60, 100
SMR	Hyttiälä	Finland	61.8474	24.2947	181	16.8, 67.2, 125
SSL	Schauinsland	Germany	47.9200	7.9200	1205	12
SVB	Svartberget	Sweden	64.2560	19.7750	235	35, 85, 150
TAC	Tacolneston	United Kingdom	52.5170	1.1386	56	54, 100, 185
TRN	Trainou	France	47.9647	2.1125	131	5, 50, 100, 180
UTO	Utö	Finland	59.7839	21.3672	8	57
WAO	Weybourne	United Kingdom	52.9500	1.1219	20	10
ZEP	Ny-Alesund	Norway	78.9067	11.8883	474	15
SOD	Sodankylä	Finland	67.367	26.631	188	Total column

**Figure 1.** Location of the CO<sub>2</sub> monitoring sites in Europe. The symbols represent the different type of stations: tall towers (red circles), coastal sites (blue diamonds), mountain sites (green triangles), other surface stations (crosses), total column site (square).

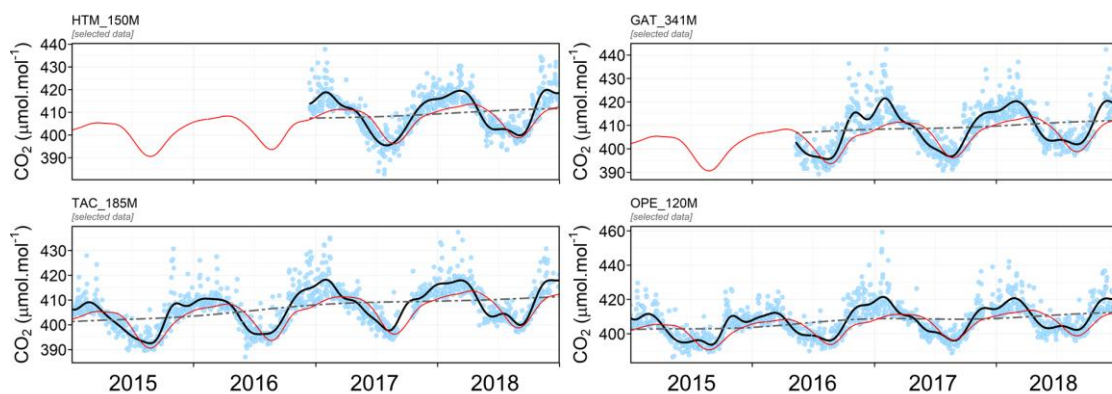
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**Figure 2.** Time series of CO<sub>2</sub> mole fractions (ppm) at 48 sites in Western Europe over the period 2009-2019. Each vertical coloured line represents a CO<sub>2</sub> daily average. The second column indicates the sampling height above the ground level, and the third column indicates whereas the station is a tall tower (Tt), coastal (Cs), mountain (Mt) or other surface site (Ot). The color code indicated the CO<sub>2</sub> mole fraction in ppm.

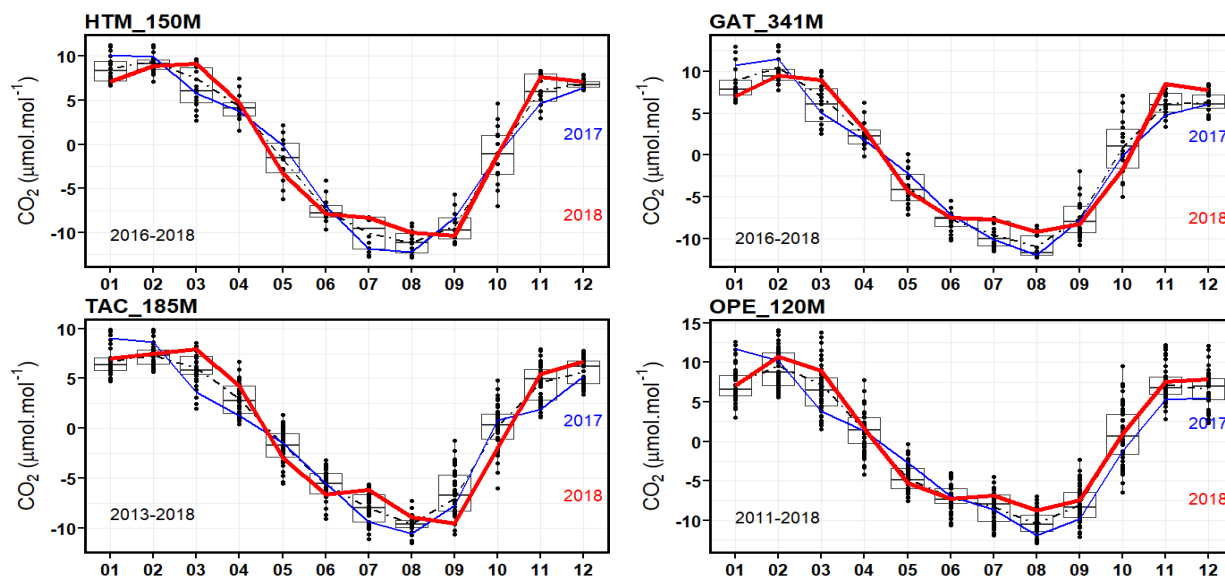


**Figure 3.** CO<sub>2</sub> time series observed at Hyltemossa (HTM, Sweden), Gartow (GAT, Germany), Tacolneston (TAC, UK) and Observatoire Pérenne de l'Environnement (OPE, France). Each blue dot corresponds to a daily average, after data selection. The black curve shows the smoothed curve of these points, and the dash-dot line the long term trends. The red curve represents the smooth curve of the CO<sub>2</sub> time series at Mace Head, Ireland in the marine sector.

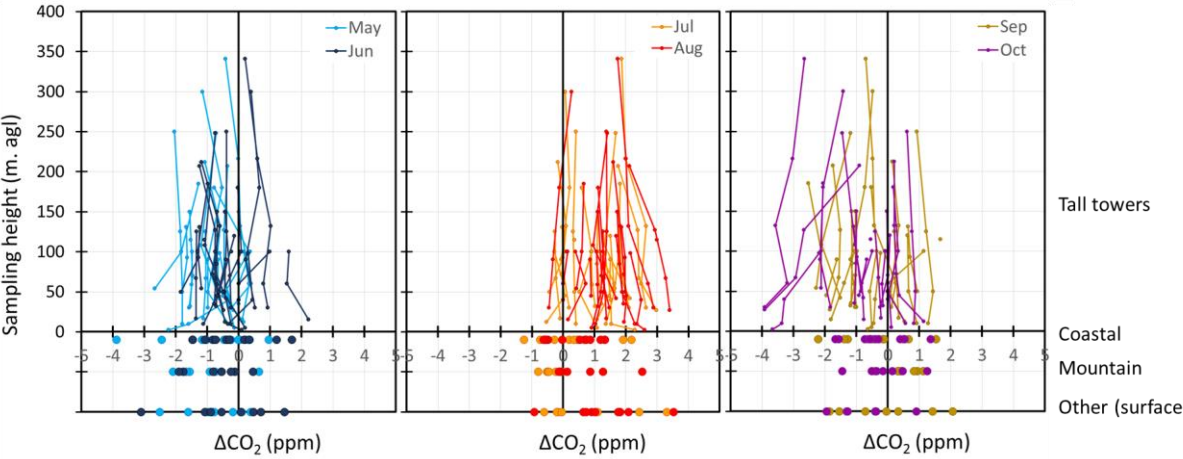




**Figure 4.** CO<sub>2</sub> seasonal cycles observed at Hyltemossa (HTM, Sweden), Gartow (GAT, Germany), Tacolneston (TAC, UK) and Observatoire Pérenne de l'Environnement (OPE, France). The 2018 cycle is shown in red, 2017 in blue, and a statistical summary of the full measurement period as box-and-whisker plots showing the median, first and third quartiles over the entire measurement period of each station, indicated in the bottom left corners of the plots. Corresponding figures for all other stations are shown in the supplementary figure S2.



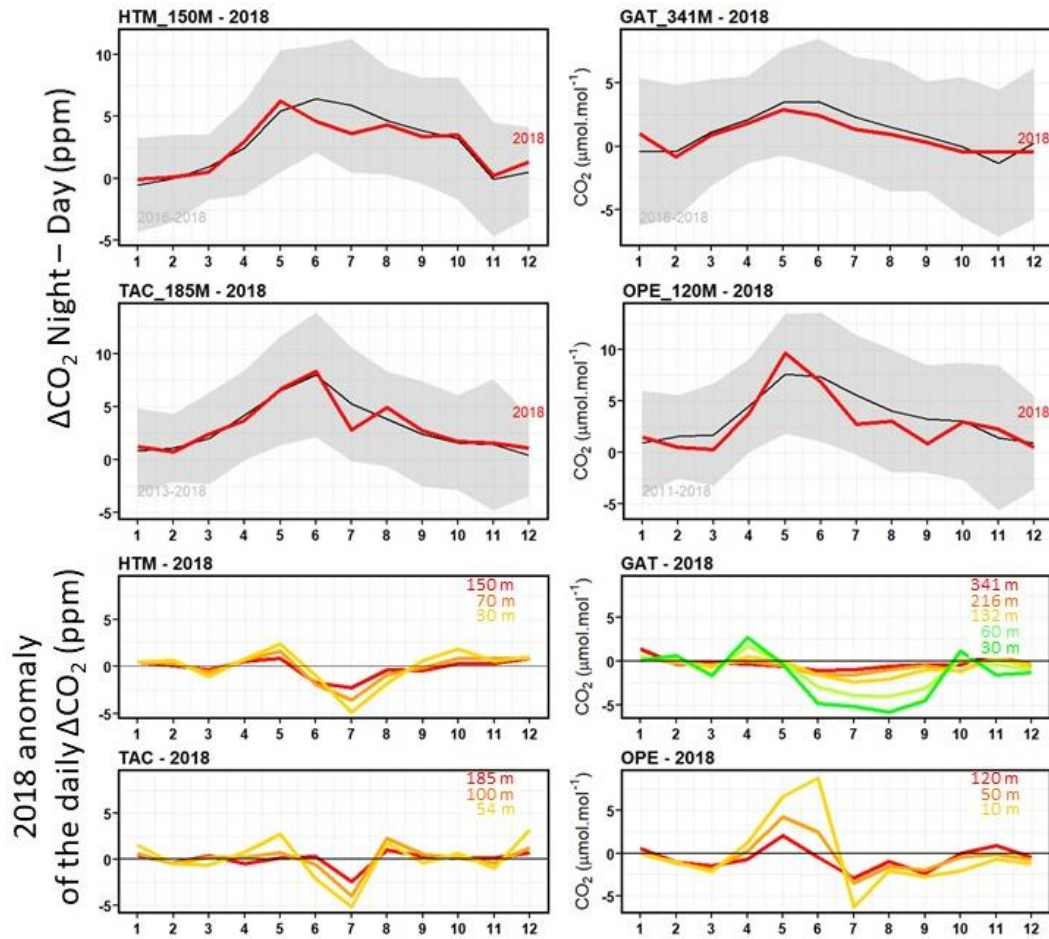
**Figure 5.** Monthly mean CO<sub>2</sub> differences anomalies for each month during May to October 2018, compared to the same month during previous years, the data being available from 2009 to 2018 with variable coverage between stations, i.e. CO<sub>2</sub> (2018) minus CO<sub>2</sub> (previous years). Upper panel shows the vertical profile of tall towers, whereas the bottom panel show separately coastal, mountain and other surface sites.



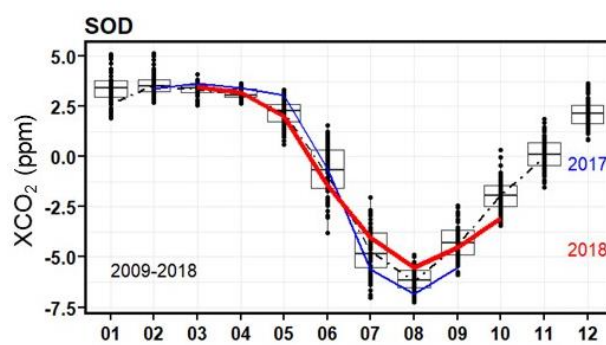


**Figure 6.** The top panel shows at four tall towers (highest levels) the amplitude of the CO<sub>2</sub> daily cycles averaged every month for all available years (black line and grey area), and for 2018 (red line).

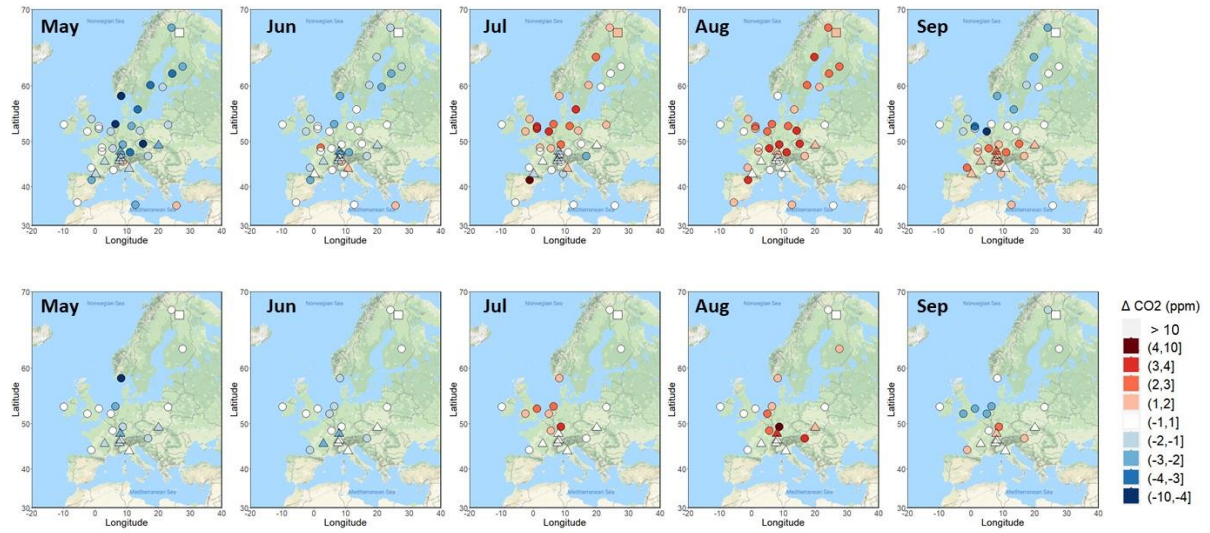
- 5 The bottom panel shows, for the same sites, the differences of CO<sub>2</sub> daily cycles between 2018 and the average over all available years. The colors represent the different sampling levels at the towers (red curves corresponds to the top panel figures).



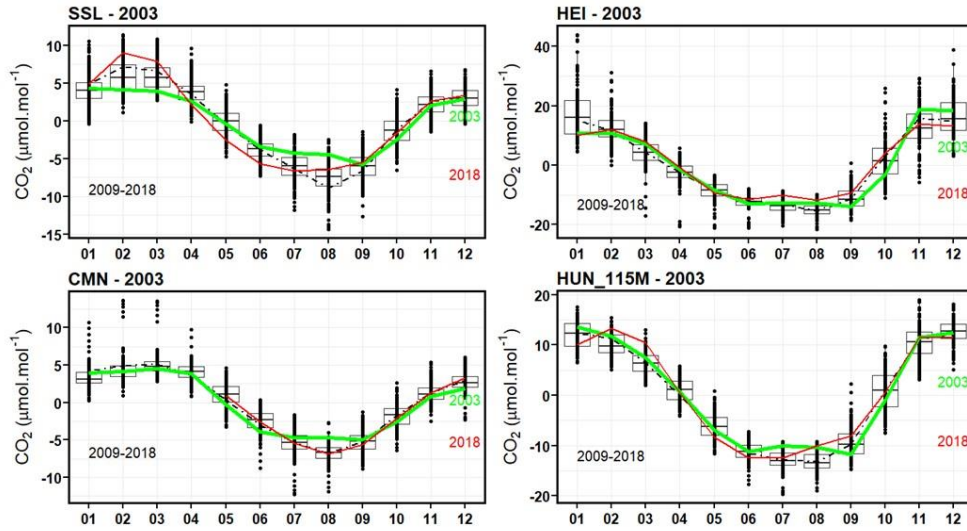
**Figure 7.** Same as figure 4 but for the CO<sub>2</sub> column-averaged dry air mole fraction of CO<sub>2</sub> (XCO<sub>2</sub>) measured at the TCCON site of Sodankylä, Finland.



**Figure 8.** Map of the monthly mean CO<sub>2</sub> differences (2018 minus 2017) from May (left) to September (right). Circles represent surface stations in lowlands. Triangles indicate the mountain site, and the square indicates a total column measurement station (TCCON). Above panels show the differences 2018 minus 2017. Below panels show differences 2018 minus 2010-2017 mean.

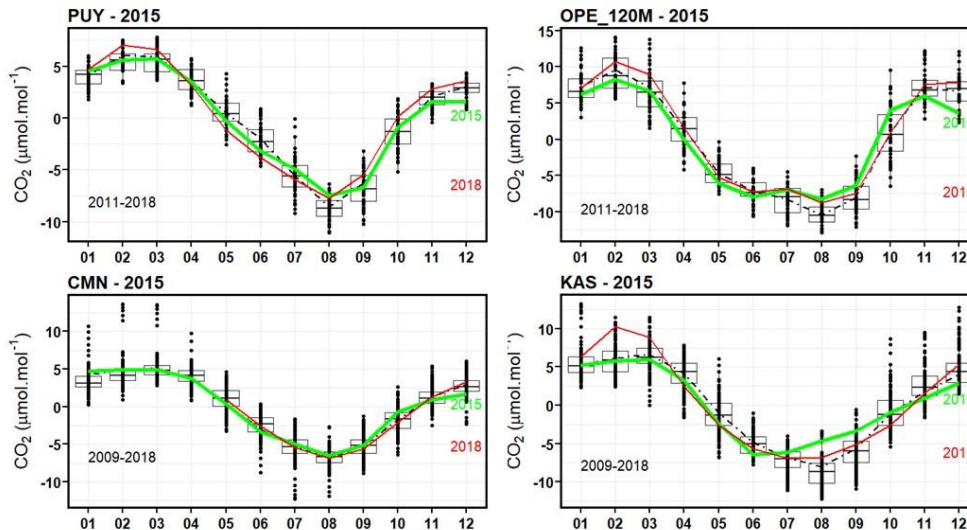


**Figure 9.** Same as figure 4 for the 2003 (green) and 2018 (red) seasonal cycles at Shauinsland (SSL, Germany), Heidelberg (HEI, Germany), Monte Cimone (CMN, Italy), and Hegyhatsall (HUN, Hungary).



5

**Figure 10.** Same as figure 4 for the 2015 (green) and 2018 (red) seasonal cycles at puy de Dôme (PUY, France), Observatoire Pérenne de l'Environnement (OPE, France), Monte Cimone (CMN, Italy), Kasprowy (KAS, Poland).



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## References

- [1] Broquet, G., Chevallier, F., Breon, F. M., Kadyrov, N., Alemanno, M., Apadula, F., Hammer, S., Haszpra, L., Meinhardt, F., Morgui, J. A., et al. 2013 Regional inversion of CO<sub>2</sub> ecosystem fluxes from atmospheric measurements: reliability of the uncertainty estimates. *Atmospheric Chemistry and Physics* **13**, 9039-9056. (DOI:DOI 10.5194/acp-13-9039-2013).
- [2] Berchet, A., Pison, I., Chevallier, F., Bousquet, P., Bonne, J. L. & Paris, J. D. 2015 Objectified quantification of uncertainties in Bayesian atmospheric inversions. *Geosci. Model Dev.* **8**, 1525-1546. (DOI:10.5194/gmd-8-1525-2015).
- [3] WMO-GAW. 2012 16th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques (GGMT-2011). (ed. G. Brailsford). Wellington, New Zealand.
- [4] Zhao, C. L. & Tans, P. P. 2006 Estimating uncertainty of the WMO mole fraction scale for carbon dioxide in air. *Journal of Geophysical Research-Atmospheres* **111**. (DOI:10.1029/2005JD006003).
- [5] Cooperative Global Atmospheric Data Integration Project 2018 Multi-laboratory compilation of atmospheric carbon dioxide data for the period 1957-2017. (ed. G. M. D. NOAA Earth System Research Laboratory), obspack\_co2\_1\_GLOBALVIEWplus\_v4.1\_2018-10-29 ed.
- [6] Artuso, F., Chamard, P., Piacentino, S., Sferlazzo, D. M., Silvestri, L. D., Sarra, A. d., Meloni, D. & Monteleone, F. 2009 Influence of transport and trends in atmospheric CO<sub>2</sub> at Lampedusa. *Atmos. Environ.* **43**, 3044-3051.
- [7] Hazan, L., Tamiewicz, J., Ramonet, M., Laurent, O. & Abbaris, A. 2016 Automatic processing of atmospheric CO<sub>2</sub> and CH<sub>4</sub> mole fractions at the ICOS Atmosphere Thematic Centre. *Atmospheric Measurement Techniques* **9**, 4719-4736. (DOI:10.5194/amt-9-4719-2016).
- [8] Kwok, C. Y., Laurent, O., Guemri, A., Philippon, C., Wastine, B., Rella, C. W., Vuillemin, C., Truong, F., Delmotte, M., Kazan, V., et al. 2015 Comprehensive laboratory and field testing of cavity ring-down spectroscopy analyzers measuring H<sub>2</sub>O, CO<sub>2</sub>, CH<sub>4</sub> and CO. *Atmospheric Measurement Techniques* **8**, 3867-3892. (DOI:10.5194/amt-8-3867-2015).
- [9] Tans, P. P., Crotwell, A. M. & Thoning, K. W. 2017 Abundances of isotopologues and calibration of CO<sub>2</sub> greenhouse gas measurements. *Atmos. Meas. Tech.* **10**, 2669-2685. (DOI:10.5194/amt-10-2669-2017).
- [10] Copernicus Climate Change Service (C3S) 2017 ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . . (ed. C. C. C. S. C. D. S. (CDS).), <https://cds.climate.copernicus.eu/cdsapp#!/home>.
- [11] Biraud, S., Ciais, P., Ramonet, M., Simmonds, P., Kazan, V., Monfray, P., O'Doherty, S., Spain, T. G. & Jennings, S. G. 2000 European greenhouse gas emissions estimated from continuous atmospheric measurements and radon 222 at Mace Head, Ireland. *Journal of Geophysical Research-Atmospheres* **105**, 1351-1366.
- [12] Geels, C., Gloor, M., Ciais, P., Bousquet, P., Peylin, P., Vermeulen, A. T., Dargaville, R., Aalto, T., Brandt, J., Christensen, J. H., et al. 2007 Comparing atmospheric transport models for future regional inversions over Europe &ndash; Part 1: mapping the atmospheric CO<sub>2</sub> signals. *Atmos. Chem. Phys.* **7**, 3461-3479. (DOI:10.5194/acp-7-3461-2007).
- [13] Gerbig, C., Körner, S. & Lin, J. C. 2008 Vertical mixing in atmospheric tracer transport models: error characterization and propagation. *Atmos. Chem. Phys.* **8**, 591-602. (DOI:10.5194/acp-8-591-2008).
- [14] Thompson, R. L., Broquet, G., Gerbig, C., Koch, T., Lang, M., Monteil, G., Munassar, S., Nickless, A., Scholze, M., Ramonet, M., et al. 2020 Changes in Net Ecosystem Exchange over Europe During the 2018 Drought Based on Atmospheric Observations. *Philosophical Transactions of the Royal Society* **This issue**.
- [15] Thoning, K. W., Tans, P. P. & Komhyr, W. D. 1989 Atmospheric carbon dioxide at Mauna Loa Observatory, 2, Analysis of the NOAA GMCC data, 1974, 1985. *Journal of Geophysical Research* **94**, 8549-8565.
- [16] Stanley, K. M., Grant, A., O'Doherty, S., Young, D., Manning, A. J., Stavert, A. R., Spain, T. G., Salameh, P. K., Harth, C. M., Simmonds, P. G., et al. 2018 Greenhouse gas measurements from a UK network of tall towers: technical description and first results. *Atmospheric Measurement Techniques* **11**, 1437-1458. (DOI:<https://doi.org/10.5194/acp-2018-839>).
- [17] Conil, S., Helle, J., Langrene, L., Laurent, O. & Ramonet, M. 2019 Continuous atmospheric CO<sub>2</sub>, CH<sub>4</sub> and CO measurements at the OPE station in France from 2011 to 2018. *Atmos. Meas. Tech. Discuss.* **In review**. (DOI:<https://doi.org/10.5194/amt-2019-128>).
- [18] Ramonet, M., Ciais, P., Aalto, T., Aulagnier, C., Chevallier, F., Cipriano, D., Conway, T. J., Haszpra, L., Kazan, V., Meinhardt, F., et al. 2010 A recent build-up of atmospheric CO<sub>2</sub> over Europe. Part 1: observed signals and possible explanations. *Tellus B*, DOI: 10.1111/j.1600-0889.2009.00442.



- [19] Pal, S., Lopez, M., Schmidt, M., Ramonet, M., Gibert, F., Xueref-Remy, I. & Ciais, P. 2015 Investigation of the atmospheric boundary layer depth variability and its impact on the Rn-222 concentration at a rural site in France. *Journal of Geophysical Research-Atmospheres* **120**, 623-643. (DOI:10.1002/2014jd022322).
- 5 [20] Koffi, E. N., Bergamaschi, P., Karstens, U., Krol, M., Segers, A., Schmidt, M., Levin, I., Vermeulen, A. T., Fisher, R. E., Kazan, V., et al. 2016 Evaluation of the boundary layer dynamics of the TM5 model over Europe. *Geoscientific Model Development* **9**, 3137-3160. (DOI:10.5194/gmd-9-3137-2016).
- [21] Aulagnier, C., Rayner, P., Ciais, P., Ramonet, M., Rivier, L. & Vautard, R. 2010 Is the recent build-up of atmospheric CO<sub>2</sub> over Europe reproduced by models : an overview with the atmospheric mesoscale transport model CHIMERE. *Tellus B*, DOI: 10.1111/j.1600-0889.2009.00443.
- 10 [22] Karstens, U., Gloor, M., Heimann, M. & Rodenbeck, C. 2006 Insights from simulations with high-resolution transport and process models on sampling of the atmosphere for constraining midlatitude land carbon sinks. *JOURNAL OF GEOPHYSICAL RESEARCH* **111**. (DOI:doi:10.1029/2005JD006278).
- [23] Patra, P. K., Law, R. M., Peters, W., Roedenbeck, C., Takigawa, M., Aulagnier, C., Baker, I., Bergmann, D. J., Bousquet, P., Brandt, J., et al. 2008 TransCom model simulations of hourly atmospheric CO<sub>2</sub>: Analysis of synoptic-scale variations for the period 2002-2003. *Global Biogeochemical Cycles* **22**, -.
- 15 [24] Smith, N. & al., e. 2020 The impact of the 2018 European summer drought on the region's terrestrial biosphere carbon fluxes from remote sensing, modelling, and data assimilation. *Philosophical Transactions of the Royal Society* **This issue**.
- [25] Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J. P., Weber, U., Reichstein, M., Fu, Z., et al. 2020 Impacts of the 2018 severe drought and heatwave in Europe: from site to continental scale. *Philosophical Transactions of the Royal Society* **This issue**.
- 20 [26] Buras, A., Rammig, A. & Zang, C. S. 2019 Quantifying impacts of the drought 2018 on European ecosystems in comparison to 2003. *Biogeosciences Discuss. in review*. (DOI:<https://doi.org/10.5194/bg-2019-286>).
- [27] Copernicus. 2019 European state of the climate 2018. (ed. E. C. f. M. R. W. F. Copernicus Climate Change Service).
- 25 [28] Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D. & Seneviratne, S. I. 2019 Concurrent 2018 Hot Extremes Across Northern Hemisphere Due to Human-Induced Climate Change. *Earth's Future* **7**, 692-703. (DOI:10.1029/2019ef001189).
- [29] Reinermann, S., Gessner, U., Asam, S., Kuenzer, C. & Dech, S. 2019 The Effect of Droughts on Vegetation Condition in Germany: An Analysis Based on Two Decades of Satellite Earth Observation Time Series and Crop Yield Statistics. *Remote Sensing* **11**, 1783.
- 30 [30] Peters, G. P., Andrew, R. M., Canadell, J. G., Friedlingstein, P., Jackson, R. B., Korsbakken, J. I., Quéré, C. L. & Peregon, A. 2019 Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nat. Clim. Chang.* (DOI:doi:10.1038/s41558-019-0659-6).
- 35 [31] Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., et al. 2019 Global Carbon Budget 2019. *Earth Syst. Sci. Data* **11**, 1783-1838. (DOI:10.5194/essd-11-1783-2019).
- [32] Yiou, P. & Nogaj, M. 2004 Extreme climatic events and weather regimes over the North Atlantic: When and where? *Geophysical Research Letters* **31**. (DOI:10.1029/2003gl019119).
- 40 [33] Hertig, E. & Jacobeit, J. 2014 Variability of weather regimes in the North Atlantic-European area: past and future. *Atmos. Sci. Let.* **15**.
- [34] Alvarez-Castro, M. C., Faranda, D. & Yiou, P. 2018 Atmospheric Dynamics Leading to West European Summer Hot Temperatures Since 1851. *Complexity* **2018**, 10. (DOI:10.1155/2018/2494509).
- [35] Kivi, R. & Heikkine, P. 2016 Fourier transform spectrometer measurements of column CO<sub>2</sub> at Sodankylä, Finland. *Geosci. Instrum. Method. Data Syst.* **5**, 271-279. (DOI:doi:10.5194/gi-5-271-2016).
- 45 [36] Rodenbeck, C., Zaehle, S., Keeling, R. & Heimann, M. 2020 Atmospheric CO<sub>2</sub> data point to heat-stimulated respiration as the dominant carbon cycle response to summer climate anomalies in Central Europe. *Philosophical Transactions of the Royal Society* **This issue**.
- [37] Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., et al. 2005 Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* **437**, 529-533.
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